ON-ORBIT CALIBRATION AND RADIOMETRIC PERFORMANCE OF ALSAT-1B OPTICAL IMAGER OVER FOUR YEARS

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ABSTRACT

As the quality of Earth observation satellite image data products depends strongly on the on-orbit calibration accuracy and consistency, on-orbit radiometric performance has to be analysed to identify any changes or drifts and radiometric characteristics have to be measured on-orbit and updated continuously during the mission lifetime to ensure the accuracy of image data and the reliability of derived information products.

This paper focuses on the on-orbit calibration and radiometric performance evaluation of the Alsat-1B optical imager by making use of in-flight data and measurements made onboard Alsat-1B over four years since its launch. The main objective of this work is to assess the optical imaging instrument's health over the first four years of the Alsat-1B mission lifetime to track and correct the on-orbit drifts in the instrument's response due to degradation induced by aging and the space environment.

The results demonstrate that during four years since the Alsat-1B launch the optical imager was performing well and producing high-quality images within the requirements specification. Alsat-1 B's mission is still operating beyond its design life.

1 INTRODUCTION

The success of any space optical earth observation mission is directly related to the performance stability of the optical imaging instruments during the mission lifetime. However, the detectors and optical systems are subject during their in-orbit lifetime to many damaging effects caused by aging and the harsh conditions (radiation and temperature) in low Earth orbit (LEO) environment threatening consequently optical imaging instruments' performance and durability [1]. Therefore, it is necessary to regularly perform on-orbit radiometric calibration and update the radiometric characteristics to correct for any drift or changes in the instrument's response over time, thus ensuring the accuracy of the radiometrically corrected image data and the consistency of derived information products [2].

On-orbit radiometric calibration for optical instruments onboard Earth observation satellites is a critical activity for guaranteeing the accuracy and reliability of the data collected by these instruments. The raw image Digital Number (DN) values of the instrument response are directly proportional to the radiance that was incident on the CCD detectors through each wanted filter, modulated by a variety of correctable instrument effects.

Radiometric calibration involves removing the instrument effects and reconstructing the true incident radiance by determining the functional relationship between the instrument response (image digital numbers, i.e., DN) and the physical units of the radiance of the scene being observed. This process is essential to ensure that the data can be used for quantitative analysis.

This paper addresses the on-orbit radiometric calibration and characterization of the Alsat-1B optical imaging instrument. It describes the complete walk-through that was undertaken to calculate the in-flight calibration coefficients to track the on-orbit changes in the CCD detectors' response and update the radiometric characteristics of the Alsat-1B optical imager by making use of in-flight data and measurements, made on-board Alsat-1B over four years since its launch.

2 BRIEF OVERVIEW OF ALSAT-1B OPTICAL IMAGER

ALITE (ALgerian Imaging TElescope) is the name given to the optical imaging payload of the Alsat-1B satellite. The Algerian medium-resolution Earth observation satellite Alsat-1B was built jointly by the Algerian Space Agency (ASAL) and Surrey Satellite Technology Ltd (SSTL). Alsat-1B carries an optical imaging payload based on a push-broom concept and provides 12-meter imagery in panchromatic (PAN) and 12/24-meter imagery in Multispectral (MS) in four bands (Red, Green, Blue, Near-Infrared (NIR)) along a 140 km wide swath and with 10/12 bits radiometric resolution. Upon completion of platform testing and initial payload checkout, the first Alsat-1B image was successfully captured and downloaded on October 14, 2016. Imager commissioning and calibration started shortly thereafter. The commissioning phase was a success and ALITE imaging camera has entered its operational phase. On September 26th, 2022, Alsat-1B, celebrated its sixth year in orbit and is still operating beyond its design life of five years.

Alsat-1B optical imager is comprised of a Telescope (optomechanics housing the lens assembly), Focal Plane Assembly FPA (housing CCD detectors assembly), and Front-End Electronics (FEE) [3]. The FPA consists of five linear CCD 21-40 arrays, each integrated with a dichroic filter to provide spectral separation into discrete bands. The CCD 21-40, supplied by Teledyne e2v Ltd, the world-leading provider of CCD technology into spacecraft, is a front-illuminated, Non-Inverted-Mode-Operation (NIMO) device, with a line of 12288x1 square pixels (photosites) of dimension 8µm x 8µm [4].

The readout consists of two interleaved registers on either side of the device, which terminate in four separate output amplifiers as shown in Figure 1. The devices also have gated anti-blooming drains, 40 additional dark reference pixels, and 16 blank elements at the end of each register section.

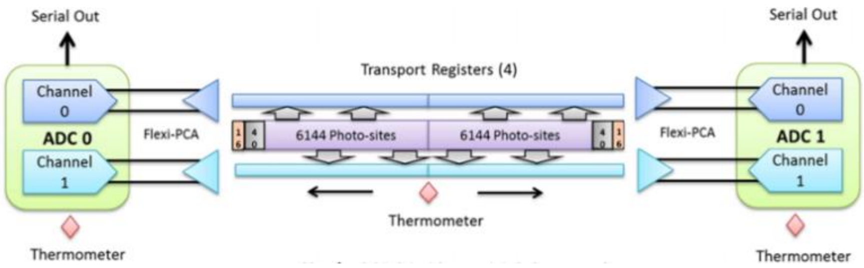


Figure 1. Single CCD 21-40. The CCD is split into two halves, with a total of 12288 light-sensitive elements. There are 40 "Dark" (covered) elements and 16 "dummy" (non-photo-sensitive) elements at each end. A total of 12496 samples will be read out per exposure (including "over-run" elements that are used in calibration). Transport registers are arranged on both sides of the photosensitive array to carry signals from "odd" and "even" elements separately.

3 IN-FLIGHT RADIOMETRIC CALIBRATION WALK-THROUGH

A prelaunch radiometric calibration of the ALITE imager has been undertaken on-ground for the following aims:

- Carrying out sufficient testing to show the instrument is meeting requirements and ensure that the instrument is operating as expected,
- Understanding instrument behavior and making required adjustments to drive electronics,
- Measuring an initial set of radiometric characteristics (dark current, pixels gain, and offset coefficients) thus establishing the initial sensor spatial response uniformity levels.

During the commissioning period that began immediately after launch, ALITE imager was subjected to a complete series of inflight calibrations. The objectives of this in-flight calibration campaign were to:

(i) Provide the final verification and the calibration coefficients,
(ii) Permit the radiometric correction of Alsat-1B imagery
(iii) Establish the on-orbit absolute radiometric calibration of the sensor.

3.1 Radiometric Calibration Model

Mathematically, inflight radiometric calibration consists of solving for variables in the linear radiometric calibration model to convert image data numbers (DNs) to physical radiance units ($W \cdot sr^{-1} \cdot m^{-2} \cdot \mu m^{-1}$).

The radiometric calibration model has the following form:

$$\mathrm{DN} = G_{abs}\, G_{rel}\, L + B \tag{1}$$

where DN is the Pixel Digital Number (Intensity), G_{abs} is the Absolute Gain, G_{rel} is the Relative Gain, L is the Pixel Spectral Radiance and B is the Sensor Bias.

The gain and bias (G_{rel} and B) are specific to a particular photodetector (pixel on the CCD).

3.2 ALITE In-Flight Radiometric Calibration Walk-Through

Fundamentally, radiometric calibration is the process of applying a bias and gain to each dark corrected pixel value to yield the top of atmosphere (ToA) spectral radiance in SI units ($W \cdot sr^{-1} \cdot m^{-2} \cdot \mu m^{-1}$).

The on-orbit radiometric calibration of the ALITE imager was performed in two sequential stages:

- Relative radiometric calibration (G_{rel} and B),
- Absolute radiometric calibration (G_{abs}).

A. *Relative Radiometric Calibration*

The objective of the relative radiometric calibration is to establish the instrument's spatial response uniformity levels by removing the detector-to-detector (pixel-to-pixel) responsivity variations within each spectral band.

The relative radiometric calibration process consists of:

1. Dark Current Correction,
2. Calibration Bias calculation after dark current subtraction,
3. Relative Calibration Gain calculation.

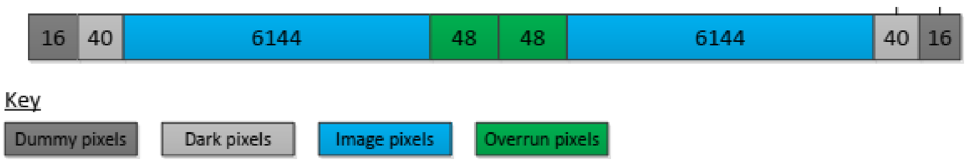
1. *Dark Current Correction*:

The dark current is the residual electrical current flowing in a photoelectric device when there is no incident illumination.

The dark current correction is a row-by-row correction technique used to account for the detectors' dark current which varies with temperature. This process is the first calibration step for all images and only uses information from the dark pixels of the specific image and scene it is being applied to, to correct for temporal differences between scenes. The dark current is determined using the dark reference pixels on the detector.

Depending on the CCD format there are a variety of dark reference pixels that can be used to determine the dark current, such as: overrun pixels, dark (shielded by a metal plate to ensure no light enters them) pixels, and test pixels.

Alsat-1B image data pixels have the following interpretation:



For Alsat-1B, the dark current correction is performed using the filtered Overrun pixels as follows:

- These 96 pixels are split into left, right, odd, and even pixels (24 of each),
- A running average over 51 lines is calculated for each of these four categories for each image line (so 25 before, 25 after, and 'this' line),
- The mean pixel value of the 51 lines * 24 left odd pixels (i.e. a total of 1224 overrun pixels) is subtracted from each left odd imaging pixel on this line,
- The above step is repeated for left even pixels, right odd pixels, and right even pixels,
- The above steps are repeated for each line in the image,
- The first and last 25 lines of each acquisition will use a smaller number of pixels as the rolling average window compresses at the start and end of the image.

2. *Calibration Bias*:

The calibration bias term is usually determined from images collected over the Pacific Ocean at night, which have proven to be as dark as deep space images for this type of analysis. The data were Dark current corrected according to the procedure of section 1.

- Complete darkness means zero radiance:
- $L = 0$, isolating the sensor bias:

$$\mathrm{DN} = \cancelto{0}{G_{abs}G_{rel}L} + B = B \tag{2}$$

3. *Relative Calibration Gain*:

The relative calibration gain term was determined from the analysis of white images collected over the snowfields of Antarctica at Dome-C. Before collection, the spacecraft was yawed to minimize the effects of uneven illumination and BRDF effects across the swath width. The data were bias subtracted using the results from section 2 of the dark image analysis. Dark subtraction used filtered overrun pixels from the center of the image.

- Snow fields create a flat field of constant radiance
- Radiance is constant at each pixel, $L = C$, isolating the relative gain (after normalization with mean):

$$DN - B = G_{abs}\, G_{rel}\, C \Longrightarrow \frac{DN-B}{\overline{(DN-B)}} = \frac{\cancel{G_{abs}}\, G_{rel}\, \cancel{C}}{\cancel{G_{abs}}\, \overline{G_{rel}}\, \cancel{C}} = G_{rel};\ \overline{G_{rel}} = 1 \tag{3}$$

B. *Absolute Radiometric Calibration*

The objective of the absolute radiometric calibration is to measure the absolute gain which is applicable to all pixels of a given spectral band. The absolute gain allows the conversion of the digital signal (DN) after relative radiometric correction into spectral radiance ($W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$). This allows comparisons between different sensors and therefore different missions.

The absolute gain was measured from images captured over the Libya-4 “Pseudo Invariant Calibration Site”, one of the most radiometrically stable locations on Earth and which is widely used for absolute radiometric calibration. The method used is based on cross-calibration with Landsat 8 OLI.

The Libya 4 data was processed with the set of calibration bias and gain values to approximate the expected absolute gain. The Radiance of Libya-4 is regularly measured by Landsat-8.

As Radiance L is known, the absolute gain can be isolated:

$$\frac{DN-B}{G_{rel}L} = G_{abs} \tag{4}$$

Band spectral differences between Landsat-8 and Alsat-1B were accounted for using Hyperion hyperspectral measurements of Libya-4.

4 EXPERIMENTAL RESULTS AND DISCUSSION

Three inflight Radiometric Calibration campaigns of the ALITE imager have been undertaken over a period of four years starting from November 2016 to December 2020.

4.1 Calibration Bias

The images used in the calibration bias analysis were collected over the Pacific Ocean at night for three different years: November 2016 during the commissioning phase, November 2019, and December 2020.

The data were dark current subtracted using the results from the dark image analysis. Dark subtraction used filtered overrun pixels from the center of the image.

Figure 2 shows calibration bias variation for the Blue band and the PAN band over four years, the other Multispectral bands show similar results as the Blue band. It can be seen that the Blue band and the PAN band gave similarly shaped plots and very stable results over the period of four years. The magnitude of the calibration bias retrieved being very consistent with standard variations of the order of 0.3 DN for the PAN band and 2.83 DN for the blue band.

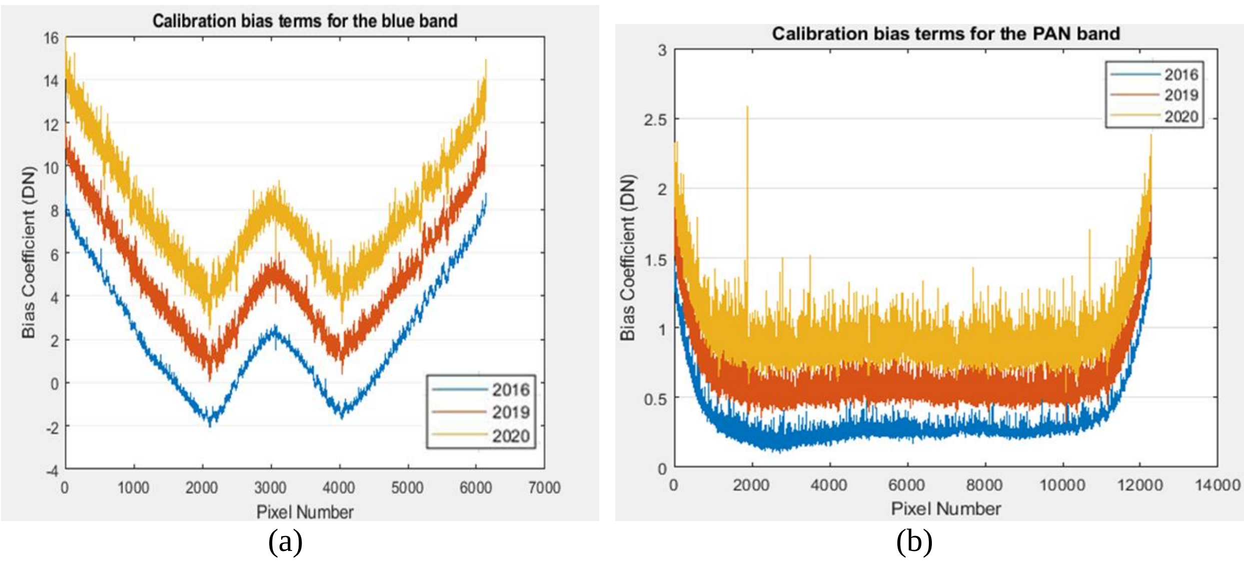


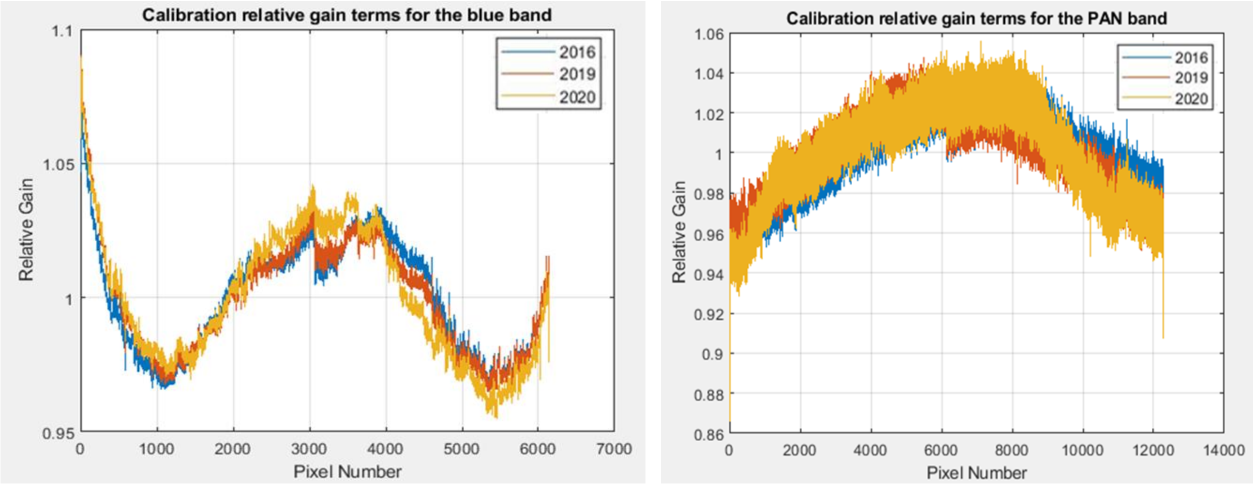
Figure 2. Multiyear Derived Calibration Bias of the blue band (a) and PAN band (b)

4.2 Relative Calibration Gain

Having derived a set of stable calibration bias values we can now turn to the next step of Relative Calibration Gain determination.

The relative calibration gain terms were determined from the analysis of white images collected over the snowfields of Antarctica at Dome-C for three different years: November 2016 during the commissioning phase, November 2019, and December 2020. The data were bias subtracted using the results from section 4.1 of the bias determination.

Figure 3 illustrates relative calibration gain variation for the Blue band and the PAN band over four years, the other Multispectral bands show similar results as the Blue band. It can be seen that the Blue band and the PAN band multiyear relative calibration gain coincide quite well and exhibit the same pattern. The differences are almost negligible.



(a) (b)

Figure 3. Multiyear Derived Calibration Bias of the blue band (a) and PAN band (b)

4.3 Absolute Calibration Gain

The absolute radiometric calibration of the ALITE imager has been performed just one time during the commissioning phase as there is no evident systematic change with time for the measured absolute gain [5].

The absolute calibration gain term was measured from the analysis of images collected over the Libya-4 "Pseudo Invariant Calibration Site", the most well understood and homogeneous radiometric calibration site.

The method used was based on cross-calibration with Landsat 8 OLI and using Hyperion hyperspectral measurements of Libya-4.

5 CONCLUSION

Alsat-1B imager has been subjected to a comprehensive series of inflight radiometric calibration over a period of four years to validate its radiometric characteristics measured on-ground, to characterize instrument stability, and to correct for systematic defects or undesirable sensor characteristics. Key inflight calibration results include stability of calibration bias to within 3 DN for MS Bands and 0.3 DN for PAN band and stability of relative calibration gain over four years. This means that the Alsat-1B imager is still meeting the requirements and performing well and producing high-quality images.

6 REFERENCES

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